Effects of Viewpoint Displacement on Navigational Performance in Virtual Environments

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Viewpoint tethering, as a way of integrating information from both egocentric and exocentric frames of reference, has been proposed as a means of supporting efficient navigation in virtual environments. In this paper, we report our latest findings on the effects of tether length on navigational performance. Twelve volunteers participated in an experiment in which they were instructed to control an aircraft-shaped cursor flying through a set of virtual tunnels and to answer questions about the environment. Experimental results showed that: (1) subjects' global awareness performance improved with an increase of tether length; and (2) neither the short tether nor the long tether supported the best local guidance performance. Rather, the best performance was observed for an intermediate length tethered display. The existence of an optimal value for this parameter provides useful guidelines for the design of navigational system interfaces.

Key Words: Dynamically tethered displays, viewpoint optimisation, local guidance, global awareness, virtual cameras, navigation, virtual environments

INTRODUCTION

As a framework for constraining viewpoint behaviour in navigational display systems, viewpoint tethering has been proposed in recent years as a means of integrating information from both egocentric and exocentric frames of reference (McCormick et al., 1998; Colquhoun & Milgram, 2000; Wang & Milgram, 2001; 2002; 2003). The concept of viewpoint tethering encompasses a display design technique that involves using a tether for virtually "attaching" the display viewpoint to an avatar. (An avatar is a remote entity under the control of the user.) Typically, the tether is defined such that the nominal position of a virtual camera is placed behind and above the avatar, looking forward. Figure 1 illustrates the spatial relationship among a virtual camera, a tether, and an avatar.

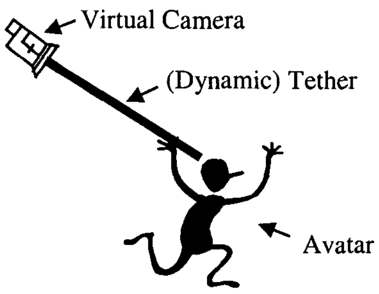

Figure 1. Spatial relationship among (dynamic) tether, virtual camera, and avatar.

Viewpoint tethering has been proposed to enhance human navigation performance by integrating information from different frames of reference. As Wickens and Prevett (1995) pointed out, *local* navigational guidance tasks (e.g., target aiming, lane following) are supported by knowledge relative to an *egocentric* frame of reference, while *global* spatial awareness tasks (e.g. route planning) are supported by knowledge relative to an *exocentric* frame of reference. In this study, local guidance is operationally defined as the task of manoeuvring along a route, while global awareness is operationally defined as the maintaining of one's position relative to other objects and the world. By removing the viewpoint from the avatar's nominal eye position while still coupling the viewpoint location and orientation with the avatar, viewpoint tethering provides a seamless integration of information from both ego and exo frames of reference.

The effect of viewpoint tethering has been investigated in a number of navigation scenarios. McCormick et al. (1998) contrasted an intermediate tethered display against an egocentric and an exocentric display in a target searching and travel task, and found that the tethered display supported superior travel performance (shorter travel time and less travel error) relative to the exocentric display. The concept of *dynamic* viewpoint tethering, in which a tether was modelled as a 6 degree of freedom mass-spring-damper system, was first proposed explicitly by Colquhoun & Milgram (2000), who explored the advantages of dynamically tethered displays in a one degree of freedom docking task. Wang & Milgram (2001) extended the experimental domain into 3D and, in a virtual tunnel navigation scenario, they found that tethered displays supported superior tracking performance relative to both ego- and exo-centric displays. In follow-up studies, Wang & Milgram (2002; 2003) contrasted tethered displays with different dynamic properties and showed that a *critically damped* dynamically tethered display resulted in the best guidance performance.

In the study reported here, efforts have been focused on investigating the effect of viewpoint *viewing distance*, in terms of the *tether length*, on both local guidance and global awareness performance in a navigational scenario.

Tether length affects the displayed information in several ways. Firstly, the tether length is one of the factors that affect *display centricity*. That is, the shorter the tether, the more egocentric the display. The extreme example of this concept is a zero length tether, which corresponds to a conventional egocentric display.

Secondly, the tether length also affects the effective *spatial resolution* of the display. Since the length of a tether determines the distance between the viewpoint and an avatar, the longer the tether length, the lower the display spatial resolution. In other words, in terms of the computer graphics representation, when the viewpoint is further away, a smaller number of pixels will be available to present a specific area of regard.

Thirdly, the length of tether is also one of the main factors that affects the amount of *preview information* that is available to the user. The longer the tether length, the more of the surrounding environment will be presented to the user, and the easier the user can control the avatar movement to accommodate the local guidance task.

In an experiment Wickens and Prevett conducted in 1995, an exocentric display with an intermediate viewing vector yielded the best tracking performance over displays with shorter and longer viewing vectors. However, their *global* awareness measurements did not yield any significant differences among the three viewing conditions. It is the goal of the current experiment to systematically address this problem and quantitatively investigate the influence of viewpoint displacement on navigational performance, especially with respect to global awareness tasks.

Two hypotheses were formulated:

1. Global awareness performance will improve with an increase of tether length; however, any performance benefits due to increasing tether length will diminish after the length reaches a certain value.

Since theoretically the tether length could extend to infinity, which would reduce spatial resolution to zero, for practical purposes we define the *maximum* tether length as the one which will permit one to observe the whole virtual world task space. It is obvious that any attempt to extend the length beyond this maximum length can not help to improve the global awareness performance. In the present study, however, we believe that an *optimal* length can be found *before* the tether reaches the maximum length and that this optimal tether length is associated with the amount of information needed to perform *both* local and global navigational tasks.

2. Due to the trade-off between preview information and spatial resolution of the display, both very short and very long tethered displays will affect local guidance performance detrimentally. Therefore, the best local guidance should be supported by a “medium” length tether.

METHOD

Participants

Twelve students (7 men, 5 women) participated in the experiment. All had normal or corrected-to-normal vision, and satisfied a standard test of stereoscopic acuity. Participants were paid $70 for their participation.

Apparatus

A Silicon Graphics O2 workstation with a 20-inch colour monitor, with 1280 x 1024 pixels of screen resolution, was used to run the simulation. The monitor was placed approximately 50 cm away from the participants' eye position. A Spaceball was used as the input device. Only three degrees of freedom (i.e. pitch, roll, and yaw) were allowed in this experiment for Spaceball control. IMAX stereoscopic shutter spectacles were used to provide a stereoscopic view. Lighting conditions were kept constant and were adjusted to minimise the glare on the monitor.

The software was developed using OpenGL. The virtual environment consisted of a cubic space which was traversed by a winding tunnel. The size of the cubic space was 5x5x5 graphical units. The virtual tunnel was rendered using wireframes with a distinctive upright orientation. The centre line of the tunnel was depicted by a red line. Eight tunnel configurations were used in the experiment, each tunnel having a unique shape and orientation. The start and end points of the tunnel were coincident with one of the eight vertices of the cubic space. Figure 2 shows an example of one of the tunnels used in the experiment.

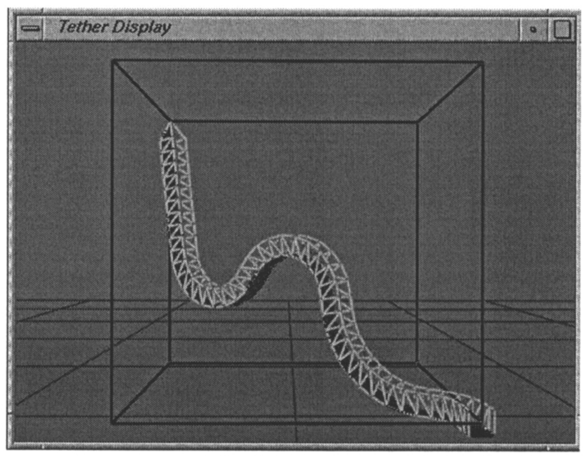

Figure 2. Profile view of the virtual environment used in the study. The grid floor is shown here to enhance the 3D perspective, but was removed in the testing condition.

Displays

Six dynamically tethered displays with different tether lengths were compared in this study. The definition of tether length ranged from 0.5 (D1) to 12 (D6) graphical units. Considering the fact that the total size of the virtual environment was 5x5x5, a tether with a length of 12 could be regarded as "very long". Figure 3a and 3b show the subjects' screen views from the two extreme tether lengths, D1 and D6. The other four tether lengths: {D2, D3, D4, D5}, corresponding to {1, 2, 4, 8} graphical units, were distributed between the two extreme conditions. All six tethers were critically damped, and the selection of spring constant and damping coefficient was based on the optimal values identified an earlier experiment (Wang & Milgram, 2002).

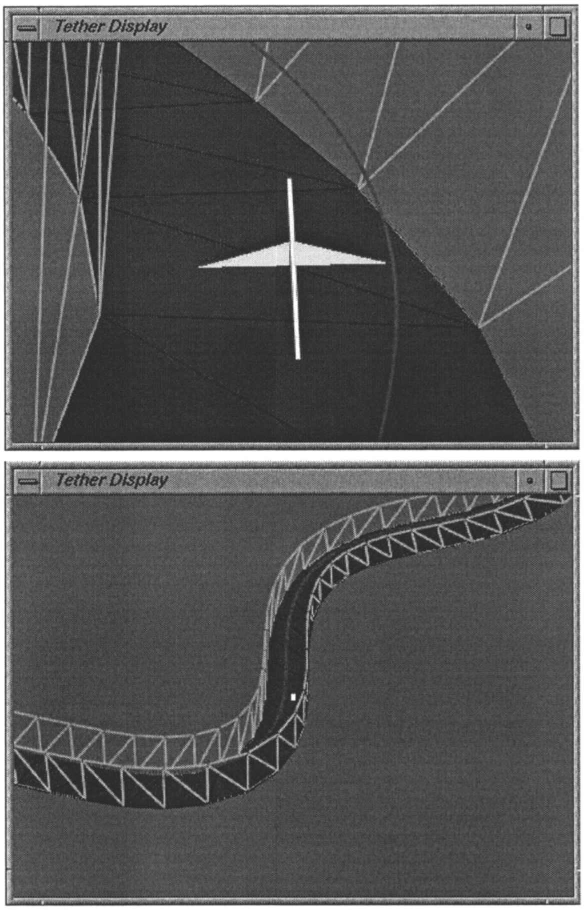

Figure 3. Screen views for (a) D1, the shortest tether (top) and (b) D6, the longest tether (bottom) presented

Tasks

Participants were required to control an avatar, represented by an airplane, flying along the centre of the virtual tunnel, while mentally keeping track of the shape of the tunnel at the same time. Before the start of each trial, the airplane was situated at the starting point of a virtual tunnel. Following on-screen instructions, participants would start a trial by pressing the space bar on the keyboard. Once a trial was initiated, the airplane began to fly forward at a constant velocity. The initial part of the tunnel was straight for all tunnel configurations. The first change of orientation of the tunnel was introduced around 5 s after the trial was started. Participants then manoeuvred to maintain the flying trajectory inside the tunnel. In order to define a unique optimal flying performance, participants were instructed to maintain the airplane along the centre line of the tunnel and keep the two wings of the airplane parallel to the tunnel floor. Changes of tunnel orientation could be compensated by pitch (climbing and diving) and roll (left and right turns) control. Yaw was needed for adjusting airplane orientation to be parallel to the tunnel floor. A trial was completed when the end of the tunnel had been reached. Each trial lasted approximately 1.5 minutes.

As a test of global awareness, after each trial participants were presented a set of eight *physical* tunnel models, built using wood frames and pipe cleaners. One among those eight models had the same shape and orientation as the virtual tunnel just traversed in the trial. Participants were required to recall the shape of the tunnel they had just flown through and pick it out from among the physical models. Participants were forced to rely solely on their memory; no further referring to the monitor was allowed.

Procedure

Participants completed six one-hour sessions individually over a three-day period. Upon arrival at the first session, they signed an informed consent form, filled in a demographic questionnaire, and were given experimental instructions. The experimenter remained in the room and answered general questions where necessary. Participants were then given a 20-minute training session on the Spaceball, followed by six experimental training trials (one on each display). During training everything was identical to the real testing conditions, except that a simplified tunnel was used.

The second session was used for spatial ability testing. Each participant was tested using the Guilford-Zimmerman Aptitude Survey (GZAS) for spatial orientation and visualisation (Guilford & Zimmerman, 1948). The duration of each test was 10 minutes.

In the ensuing four sessions, participants completed four blocks, each comprising 24 experimental trials. Root Mean Square (RMS) tracking errors were used to measure performance on the local guidance subtask. A perfect score (zero error) meant that the participant had flown the airplane perfectly along the centre of the tunnel, with the two wings parallel to the tunnel floor at all time. The tunnel shape recognition test was then carried out and the accuracy of these judgements was used as an indication of the completeness of the cognitive map developed (Golledge, 1999), i.e. as a measure of global awareness performance.

RESULTS

During the two-week testing period, twelve participants finished a total of 1152 trials. Raw data were tabulated and analyzed using Minitab. The analysis focused on two main measures: (1) overall RMS errors produced on each display condition; and (2) tunnel shape recognition scores.

Local guidance performance

A main effect of display was found for the overall RMS error score (including both position and orientation errors) ($F(5,1080) = 9.94$, $p<0.001$). Local guidance performance was best supported by D3, which corresponded to a tether length of 2 graphical units and which could be considered an "intermediate" length tether in the context of the present study, as shown in Figure 4. A Tukey pair-wise comparison showed that local guidance performance with D3 was significantly better than with the other displays, except D2. As anticipated, therefore, local guidance performance deteriorated consistently as tether length deviated in either direction from the observed optimal length (2 graphical units in the present case).

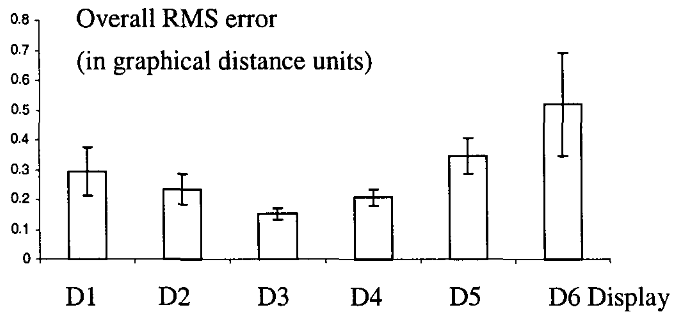

Figure 4. Local guidance performance (overall RMS error) across all six tethers, with increasing tether length from left to right.

Global awareness performance

As shown in Figure 5, participants' tunnel shape recognition scores demonstrated an essentially monotonic trend of performance improvement with increase of tether length, from a low score of 54% for D1 (the shortest tether) to a high score of 82% for D6 (the longest tether). ANOVA confirmed a main effect of display ($F(5,1080) = 13.72$, $p<0.001$), and a Tukey pair-wise comparison revealed that global awareness performance scores for D1 and D2 were significantly lower than those for the remaining four tether lengths. No significant differences were found among the four longer tether displays (D3 - D6).

Individual differences

The analysis of participants' GZAS orientation and visualisation test scores revealed large individual differences. However, regression analysis between participants' global awareness performance scores (percentage of correct tunnel shape recognition scores) and their spatial ability test scores failed to show a significant correlation, thus suggesting that the pattern observed in Figure 5 was related primarily to tether length and was not confounded with individual differences.

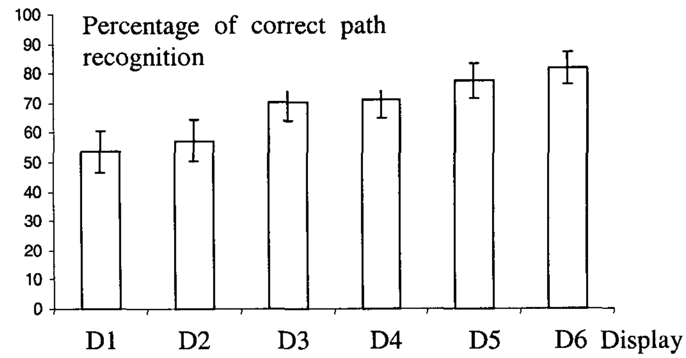

Figure 5. Global awareness performance (percentage of correct tunnel shape recognition judgments) across six displays with increasing tether lengths from left to right.

DISCUSSION

Tether length and preview information

Preview information refers to information or knowledge that helps users to foresee impending dynamic changes of task requirements and that allows users adapt to such changes by adjusting their control inputs accordingly. In the present study, preview information is manifested mainly by upcoming changes in flight trajectory defined by the tunnel shape and is determined mainly by the available field of view. The amount of preview information in a tethered display is determined by three factors: the viewing angle of the viewpoint, the length of the tether, and the initial nominal position and orientation of the viewpoint.

In the present study, a constant viewing angle was maintained, by fixing the equivalent lens setting and the viewing angles (both horizontal and virtual) for all viewpoint configurations. The length of the tether, which defined the distance between the viewpoint and the avatar, was thus the major factor that determined the effective display field of view for each case. The longer the tether, the more surrounding information was provided in the display. Figure 6 illustrates how elongating the tether length increased the display field of view.

One possible criticism of our experiment is that we did not take into consideration the viewpoint azimuth and elevation angles when designing the dynamic tethers. (In other words, ideal azimuth and elevation angles might be closely associated with the type of avatar used for a particular system and a particular task.) Since that factor was beyond the scope of this research, a single initial viewpoint configuration was maintained for all the tethered displays studied. Further research is needed to consider these additional factors.

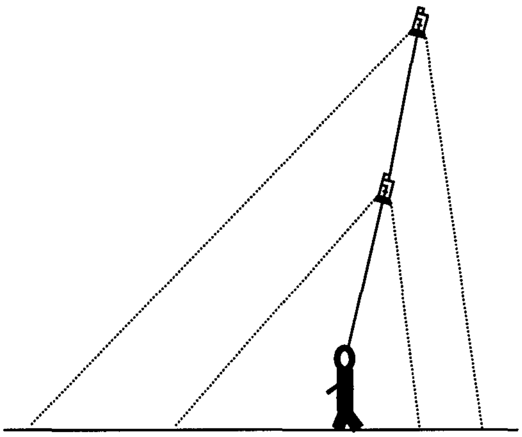

Figure 6. Sketch illustrating the different amount of field of view caused by viewpoint configurations with a constant viewing angles but different tether length.

Optimal tether length

The local guidance performance showed that the optimal tethered display for the present task was display D3, which had a length of 2 graphical units. Our experimental conclusion is thus that the best overall navigational performance is supported by an "intermediate" length tether. The use of the word *intermediate* here is to emphasise the fact that *optimal* tether length is not coincident with *extreme* tether length. This conclusion is supported by the expected trade-off between preview information and the display spatial resolution.

Considering the fact that the tether lengths for the current experiment ranged from 0 (egocentric case) to 15 (exocentric case, in which the viewpoint encompassed the whole cubic environment) graphical units, an optimal tether length of 2 graphical units lies towards the short end of the tether range. As shown in Figure 4, this optimal tether length was determined mainly by the local guidance task, the only part of the experiment for which participants reported any difficulties. On the basis of the navigation framework proposed by Wickens and Prevett (1995), it is predictable that an optimal display for supporting the experimental tasks such as the one employed here would lie towards the egocentric end of the display centricity continuum. (Milgram & Colquhoun, 1999). The finding of a relatively short optimal tether thus provides direct support of the validity of that framework.

Using the same principles, further predictions of optimal tether length can be made with respect to task difficulties. For example, it is predicted that optimal tether length will increase if the control difficulties associated with a local guidance task are reduced, for example, by slowing down the avatar's velocity, or reducing the input forcing function frequency, or reducing the number of control degrees of freedom, or improving control-display compatibility. Furthermore, optimal tether length should also increase if the importance of global awareness increases, for example if the complexity of the environments increases, or if route planning becomes more important. This is because tradeoffs between local guidance and global awareness tasks impose differential requirements for integrating information between egocentric and exocentric frames of reference. In this report we have shown the potential flexibility offered by dynamic viewpoint tethering for supporting navigation efficiency in this respect.

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